TITLE OF THE INVENTION

FIBER-PIGTAILED ASSEMBLY

BACKGROUND OF THE INVENTION

The present invention relates to coupling light onto an optical detector, and more particularly to a fiber-pigtailed assembly that couples light from an optical fiber onto an optical detector having a relatively large area such that the polarization-dependent responsivity and back reflection are very low.

Polarization-dependent responsivity (PDR) is the ratio of the maximum photo-current divided by the minimum photo-current generated in an optical detector for a given flux of photons over all possible states of polarization and correlates to polarization-dependent loss (PDL). Ideally PDR is zero dB. Reflectivity is the flux of photons that travel backward to the optical source divided by the flux of photons impinging upon the optical detector, usually expressed in dB. Ideally the reflectivity is minus infinite dB.

Low back reflection and low PDR tend to be difficult to achieve simultaneously. Usually methods that improve one make the other worse. For some types of test equipment that measure the characteristics of fiber-optic components it is important to have an optical detector with both low reflectivity and low PDR. Typical requirements for back reflection and PDR are -45 dB and 0.03 dB, respectively. Extraordinary requirements are -65 dB and 0.003 dB, respectively.

While these requirements are important for test-and-measurement (T&M) applications, they are not typically necessary for the majority of people who use fiber-pigtailed detectors. Since T&M applications are a small

percentage of the overall market for such devices, it is often difficult or impossible to find a company that can or will build such a device for the limited T&M market.

A common method of reducing back reflection is to use various optical coatings that are designed for low reflectance. These coatings are based on interference, however, and so exhibit wavelength dependence. Even at the optimized wavelength, coatings have difficulty achieving the best-desired specifications. For applications involving wide-band detection, i.e., over many hundreds of nanometers of wavelength, the performance of such coatings is a serious limitation.

Another common method of achieving low back reflection is to tilt the surface of the optical detector relative to the input fiber. The resulting reflected light is thus angled such that it fails to couple to guided fiber modes and is quickly lost. Unlike coatings, tilted surfaces are inherently broadband, resulting in very low reflectivity. Tilting the optical surface, however, introduces PDR. This is largely the result of the fact that the power in the reflected light from a tilted surface is a function of the state of polarization. This is often the source of the low PDR/low back reflection trade off.

In T&M applications using photodetectors to measure optical power requirements typically calls for low back reflection to help avoid instabilities that result from feedback into the laser source, while also calling for low PDR. The problem is that the optimum way of achieving low back reflection, as indicated above, is to use tilted surfaces, yet tilted surfaces introduce polarization dependencies. This problem is amplified in pigtailed optical

detectors because the optical pigtail acts like a weak Fabry-Perot resonator, with a birefringent medium (the fiber itself) between mirrors (the reflective ends of the fiber pigtail).

In a Fabry-Perot resonator without birefringence between the mirrors the transmitted and reflected fields add coherently to produce the characteristic wavelength-dependent transmission of these resonators. The introduction of a birefringent material between the mirrors causes relative rotation between reflection/transmission terms that ordinarily would add. However rotation of these terms interferes with their ability to coherently mix, resulting in modulation of the transmitted optical power, i.e., the modulation is a function of the birefringence and wavelength. Thus a simple component made of parts that individually have no polarization-dependent loss (PDL) may exhibit significant PDL. When pigtailed to the optical detector, the fiber assembly and detector together constitute a device that may show considerable PDR. Assemblies with normal incidence, where PDL might be expected to be least, actually show more polarization dependence than those with tilted surfaces. This is because the PDL of the weak Fabry-Perot resonator inherent in the fiber pigtail is amplified by the relatively strong reflection at normal incidence.

What is desired is a fiber-pigtail assembly for an optical detector that provides both low PDR and low back reflection sufficient to meet or exceed even extraordinary specifications.

BRIEF SUMMARY OF THE INVENTION

Accordingly the present invention provides a fiber-pigtailed assembly for an optical detector that has both low polarization-dependent responsivity (PDR) and low back reflection. The end of a fiber pigtail is held in a ferrule near the detector and is beveled at an angle so that reflections from the ferrule beveled end are not coupled into guided modes back to a light source. The surface of the detector is tilted in a different plane from that of the bevel at the end of the ferrule. Finally the planes of incidence at the end of the ferrule and at the detector are defined in such a way – nearly orthogonal – that the PDR from these surfaces cancel each other. The PDL is essentially eliminated by rotation of the surface of the detector and/or the beveled end of the fiber pigtail relative to each other and by tilting of the surface of the detector, which tilt may be pre-calculated and fixed or may be adjustable. Low reflection and essentially zero PDL also may be achieved at a coupler end of the fiber pigtail having an external optical fiber with a beveled end adjacent to the coupling end of the fiber pigtail having a complementary bevel. An intermediate ferrule is coupled between the coupling end of the fiber pigtail and an output ferrule. The bevels at each end of the intermediate ferrule have approximately the same angle, but are rotated approximately orthogonally to each other. The output ferrule has a corresponding bevel to that of the intermediate ferrule. The bevels reduce back reflections, while the orthogonal bevel interfaces act to zero out the PDL introduced by the bevels.

The objects, advantages and other novel features of the present invention are apparent from the following detailed description when read in conjunction with the appended claims and attached drawing.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

Fig. 1 is a vector diagram view illustrating PDL cancellation to minimize PDR according to the present invention.

Fig. 2 is a side view of a fiber-pigtailed assembly according to the present invention.

Fig. 3 is a top view of the fiber-pigtailed assembly of Fig. 2.

Fig. 4 is another side view of the fiber-pigtailed assembly illustrating tilt according to the present invention.

Fig. 5 is a graphic view showing the effect of detector tilt on PDL according to the present invention.

Fig. 6 is a block diagram view of a system for adjusting the fiber-pigtailed assembly according to the present invention.

Fig. 7 is a partial cross-sectional top view of a fiber coupler for the fiber-pigtailed assembly according to the present invention.

Fig. 8 is a partial cross-sectional side view of the fiber coupler of Fig. 7.

Fig. 9 is a graphic view illustrating the effect of bevel angle at the end of an optical fiber on PDL.

Fig. 10 is a graphic view illustrating the effect of the difference between bevel angles at opposite ends of an optical fiber on PDL.

DETAILED DESCRIPTION OF THE INVENTION

As discussed above, merely butting a flat end of a fiber pigtail to a detection surface of an optical detector results in reflection from the flat end that is fed back to an optical source, resulting in unwanted modulation of the optical source. Also the additional reflection from the other end of the fiber pigtail which is coupled to an external optical fiber sets up a birefringent cavity which is polarization dependent, i.e., introduces polarization-dependent loss (PDL) in the fiber pigtail. Therefore to reduce back reflections the end of the fiber pigtail adjacent to the detection surface is beveled. However this introduces a fixed amount of PDL into the optical detector. This may be represented as a fixed vector **34** as shown in Fig. 1. Tilting the detector surface approximately orthogonal to the plane of the bevel of the fiber pigtail introduces a variable magnitude PDL as a function of the tilt angle in the opposite direction, as shown by the variable vector **36**. There may be an additional, very small amount of variable PDL due to the orientation of the detector surface relative to the beveled end of the fiber pigtail, which is represented by a small dotted vector **38**. This is compensated for by the rotation of the detector surface relative to the beveled end of the fiber pigtail to produce a new fixed PDL vector **40** which, when added to the small vector **38**, produces a resultant vector along the axis. The resultant vector is compensated for by the variable vector **36** as described above to essentially eliminate PDL.

Referring now to Figs. 2 and 3 one possible embodiment is shown having a housing **10** with a fiber holding portion **12** and an optical detector holding portion **14** coupled together by a connecting portion **16** so that there is an interior gap **18** between interior surfaces **20, 22**. An optical detector **24** is mounted in the optical detector holding portion **14** so that its detection surface **26** faces the gap **18**. An end of a fiber pigtail **28** is secured by a ferrule **30** in the fiber holding portion **12** such that the end is adjacent to the detection surface **26** in the gap **18**. The end of the ferrule **30** and fiber pigtail **28** adjacent to the detection surface **26** is beveled at an angle. A means, such as a screw **32** through the optical detector holding portion **14** with its tip contacting the interior surface **20** of the fiber holding portion **12**, may be provided to "tilt" the optical detector **24** relative to the end of the ferrule **30**, as shown in Fig. 4, about a point in the connecting portion **16** that is in this instance flexible. Also the ferrule **30** may be rotated slightly to achieve an optimum position, as explained below, with the plane of the bevel being approximately orthogonal to the angle α of the tilt. For example if the bevel angle at the end of the ferrule **30** is 20 degrees, based on theoretical calculations and actual empirical data, to achieve essentially zero PDL requires a tilt for the optical detector **24** of about 17.96 degrees, as shown in Fig. 5, and a rotation of about -36.304 degrees. The rotation may be achieved by rotating the ferrule **30** rather than the detector **24**. Whatever the bevel angle on the ferrule **30**, there is some combination of tilt and rotation (equivalent to rotation of the detector **24**) that results in essentially zero PDL.

The result is to zero out (< 0.001 dB) any polarization-dependent effects in the fiber-pigtailed assembly for the optical detector while having low back reflection (< -80 dB). The distance of the fiber pigtail **28** from the large-area detector surface **26** is dependent upon the spot size as a function of distance from the end of the fiber pigtail. Using a ray model for a large area detector surface **26** with a 500 micron area and a 62.5 micron cross-sectional area multi-mode fiber pigtail **28**, the beveled end of the fiber pigtail should be within about 1.5 mm of the detector surface.

Adjustment of the fiber-pigtailed optical detector may be achieved by providing, as shown in Fig. 6, a source of different polarization states of light, such as light from a laser source **52** through a polarization scrambler **54**, in a short period of time (<< 1 sec.) into an external optical fiber **56**. The external optical fiber **56** is coupled to the fiber-pigtailed assembly **10** of the optical detector and the electrical output is amplified by an amplifier **58** and displayed on an oscilloscope **60**. This provides an electrical signal **62** having a certain peak-to-peak amplitude. The ferrule **30** may be rotated to minimize the peak-to-peak amplitude, and then the tilt may be adjusted by the tilt means **32** to further minimize the peak-to-peak amplitude. These steps may be iterated as necessary to achieve a minimum peak-to-peak amplitude for the electrical signal **62** which represents essentially zero PDL. Where the housing **10** has a fixed tilt angle (based on pre-calculations) between the fiber and detector portions **12, 14** only rotation is adjusted, lessening the adjustment time in the manufacturing of the fiber pigtailed assembly.

In a test and measurement instrument another source of PDL and back reflection is the coupling of the external optical fiber, typically a smaller diameter single-mode fiber, to the fiber-pigtailed assembly. Current optical couplers provide physical contact between the external optical fiber and the fiber pigtail **28**. It is desired also to have low back reflection and PDL at the coupler. The coupler described here may take the form of a sleeve **40**, as shown in Figs. 7 and 8, having three optical ferrules in series. An input ferrule **42** is attached to the end of an external optical fiber **44** of a system to be measured. The input ferrule **42** has a beveled end at the end of the external optical fiber **44**. An intermediate ferrule **46** contains an optical fiber corresponding to the fiber pigtail **28** and has both ends beveled, with the bevels being in approximately orthogonal planes. The intermediate ferrule **46** is placed adjacent the input ferrule **42** so that the adjacent ends are parallel and close, but not necessarily in physical contact. Likewise an output ferrule **50** is provided on the coupling end of the fiber pigtail **28** adjacent to the intermediate ferrule **46**, and also has a beveled end. The output ferrule **50** is placed adjacent to the intermediate ferrule **42** so that the beveled ends are parallel and preferably in physical contact. A non-contact coupling is preferred between the external optical fiber **44** and the optical fiber of the intermediate ferrule **46**. Fig. 9 shows that for an interface between the ferrules **42, 46, 50** the PDL is a function of the bevel angle at the interface surface. As is apparent, to minimize PDL the bevel angle needs to be relatively small, but sufficient to reduce back reflection to specified limits. To

essentially eliminate all PDL the four interfaces of the ferrules need to be accurately aligned. Fig. 10 shows the residual PDL in the intermediate ferrule **46** when the bevel angle for one pair of interfaces **42/46** is different from the bevel angle of the other pair **46/50**. The objective is to have approximately 0.1 degree accuracy in maintaining a common bevel angle, such as 7 degrees for this example, and 0.9 degree accuracy in achieving the orthogonal configuration between the interfaces on opposing ends of the intermediate ferrule **46**.

Coupling the external optical fiber **44**, generally a smaller diameter single-mode fiber, to the optical fiber of the intermediate ferrule **46** requires alignment to within about 0.5 mm between the respective fibers based on the spot size from the smaller diameter fiber to the larger.

Although the drawing figures show a configuration where the housing **10** has two portions **12, 14** coupled by a connecting portion **16** that may be flexible so that the tilt of the optical detector **26** relative to the beveled end of the fiber ferrule **30** is adjustable, the housing may be rigid with a fixed angle of tilt for the detector and fiber ferrule based on pre-calculations, as indicated above. In that case only rotation of the fiber ferrule **30** is used to provide adjustment.

Thus the present invention provides a fiber-pigtailed assembly for an optical detector with minimal back reflection and PDR by having a detector end of an optical fiber with a bevel angle adjacent to the surface of the optical detector, the optical detector being tilted and rotated relative to the end of the

optical fiber for both minimum back reflection and PDR, and may include having a coupling end of the optical fiber for the fiber-pigtailed assembly in a coupler having an intermediate ferrule with equal beveled angles on opposing ends situated orthogonally to each other such that they are parallel to respective ends of input and output ferrules of the coupler having matching bevel angles to couple light from an external optical fiber in the input ferrule to the optical fiber in the output ferrule for transmission to the detector.